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Life cycle evaluation of greenhouse gas emissions of a highway tunnel: A case study in China

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ABSTRACT

The purpose of this paper is to evaluate greenhouse gas (GHG) emissions of a Chinese highway tunnel in the life cycle. Life cycle assessment (LCA) method is adopted in the paper. Based on rock mass classification and pavement categories, five different functional units have been proposed for the first time. The system boundaries, processes and assumptions are defined. The study results indicate: 1) the GHG emissions of a double-track four-lane Chinese highway tunnel in 100 years can be up to 375.5 thousand tons of $CO_{2\ eq}$. Cement and electricity contribute to more than 80% of the total emissions in all functional units. 2) The construction stage, operation stage and maintenance stage emit 30.89%, 56.12% and 12.99% of the total GHG respectively. During the construction stage, casting and lining, rock support and road work are the top three GHG emission processes. 3) Rock conditions are discovered to be an important factor of affecting GHG emissions in tunnels. The GHG emissions of the 1-m Chinese highway tunnel are between 82 t to 113 t $CO_{2\ eq}$. With the increase of rock mass grades, GHG emissions rapidly rise if the pavement design stays the same. The emission differences among the functional units are mainly from materials. 4) Asphalt pavements tend to generate more GHG emissions than concrete pavement due to the more frequent replacements of asphalt pavements. This paper investigates the influences of rock conditions and pavement types on the GHG emissions of Chinese tunnels in the life cycle, which can provide a scientific reference for policy making of the Chinese government.

1. Introduction

Large amounts of greenhouse gas (GHG) are emitted during in the construction stage, operation stage, maintenance stage and material production of a highway (Cass and Mukherjee, 2011). The construction sector is reported to be the forefront resource use driver in European Union (Steger and Bleischwitz, 2011). Direct GHG emissions in highway transportation also play a major role in transportation. Some literature on the life cycle assessment (LCA) of transportation infrastructure have already existed. (e.g. Chester and Horvath, 2009; Stripple, 2001; Jonsson, 2007; Federici et al., 2003; Karlsson and Carlson, 2010; Moretti et al., 2017a; 2018; etc.). Tunnels are regarded as the highest energy and material density sector in transportation infrastructures (Miliutenko et al., 2012). According to GHG emission calculations on California's high-speed railway system completed by Chang and Kendall, GHG emissions by tunnels contributed 60% to total GHG emissions excluding tunnel ventilation and lighting. The lengths of the tunnels constitute only about 15% of the route (Chang and Kendall, 2011). Therefore, LCA studies of GHG emissions from tunnels are of great significance. However, LCA studies of road tunnels have rarely been reported except for the researches done by Miliutenko et al. (2012): they evaluated the GHG emissions of a Swedish tunnel, and Huang et al. (2015): they analyzed the life cycle effect of a standard Norwegian road tunnel. Hammervold (2014) reported the average life cycle Global Warming Potential (GWP) effect of a Norwegian tunnel. Potting et al.

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(2013) researched the life cycle effect of Norwegian tunnel in the early planning stage. But the tunnel designs and analysis time horizon (ATH) of these cases are not the same.

According to the statistical bulletin published by the Chinese transportation industry, the total mileage of all Chinese road tunnels had exceeded 10 thousand kilometers in 2014 (MOT, 2015). The mileage is expected to approach 18 thousand kilometers by 2020. There is no doubt that the scale of construction and speed of Chinese tunneling industry are in the lead worldwide (Jiang, 2017). Under the mandate of rapid development in the tunnel construction, GHG emission evaluation of Chinese road tunnels has strategic importance for emission reduction. According to the "Executive Meeting of the Chinese State Council", the GHG emissions per unit of gross domestic product (GDP) of China in 2020 will drop by 40%–50% relative to that in 2005. The roadmap listed is a binding force for medium-term and long-term planning of the national economy and social development. However, it is found that no life cycle GHG emission research of tunnels was yet completed in China after literature research.

Rock mass grade is the basis for choosing the construction method and support structure design (Jia and Tang, 2008). It is also the foundation of selecting lining structure types, size and material consumption criteria, which should be taken into consideration of LCA studies of tunnel GHG emissions. When a LCA research of highway tunnel is conducted, different rock mass should correspond to different functional units. According to the integrality degree and strength of the rock, rock mass is divided into six grades. The strength and integrality of the surrounding rock decreases from Grade I to VI. (China Merchants Chongqing Communications Technology Research & Design Institute Co. LTD, 2004). The physical mechanical data of Chinese rock mass classification are shown in Table 1.

However, the influence of rock mass grades on the GHG emissions has rarely been reported (Xu et al., 2019). Huang et al. (2015) defined the rock as medium rock blast ability, ignoring the influence of rock mass grades. What should be noted is that tunnels are buried inside stratums which are different from roadways and buildings. Rock mass conditions have apparent impacts on resource inputs and energy inputs for tunnels.

In order to solve the dilemma of poor life cycle assessments in tunnel, firstly, the GHG emission level of a Chinese highway tunnel has been evaluated and a consumption inventory of materials and energies of the Chinese highway tunnel has been established. Secondly, the influences of rock mass grades on roadway tunnel GHG emissions have been proposed. Since China covers a vast land area with geologically varying conditions, one tunnel site may have different geological conditions. In this study, with the rock mass grades taken into account, the hotspots and GHG emission reduction potentials of Chinese highway tunnels haven been analyzed. Furthermore, the key influence factors of GHG emissions for Chinese highway tunnels as well as emission reduction strategies have been concluded.

The structure of this paper is shown as follows. Section 2 describes the methodology, model and data source of the study. Section 3 discusses the results of the analysis. Section 4 compares this study with previous works and discusses the significance of highway tunnel sector on national carbon reduction and the strategies of reducing GHG emissions for Chinese highway tunnels. Limitations of this paper are clarified. Section 5 concludes the findings.

2. Methodology

The LCA study follows the Chinese standards 'GB/T 24040 and GB/T 24044' which are equivalent to ISO 14040/14044 methodology (Chen et al., 2009; Standardization Administration of China, 2008). The LCA modelling were conducted using Excel files. The foreground data was obtained from the tender, *JTGT B06-02-2007 Highway Engineering Budget Quota* (Quota station for highway engineering MOT, 2007) and the cost budget of the national unified construction machine team (The PRC MOHURD, 2011). *Highway Engineering Budget Quota* is a professional quota for Chinese highway engineering. Given the reasonable construction organization and normal construction conditions, the quota is expressed by the amount of manual work, material and machine-team. Road work, tunnel engineering, transportation and material collection constitute to this quota. The background data were from the Chinese Life Cycle Database (CLCD) and the existing literature in China.

2.1. Study purpose and scope

In this paper, the Chinese highway tunnel is defined as a double-track four-lane tunnel. Drilling and blasting method is adopted in tunnel excavation, which is common in Chinese tunnel construction. The tunnel is located in the mountainous area of Sichuan Province, China. Basic parameters of the tunnel are shown in Table 2. The tunnel section designs in different surrounding rocks are shown in Fig. 1.

2.2. Functional unit

Rock mass grades in the study include Grade III, IV, and V. Different tunnel lining designs are applied in accordance with different rock mass grades, while the pavement designs for different zones in this tunnel are not directly influenced by the rock mass grades. Asphalt pavement is paved in the tunnel entrance section and the exit section (1000 m in length). Concrete pavement

Table 2
Basic parameters of the tunnel.

Design parameter	Value and unit
Tunnel length	4000 m
Cross section	78.23 m^2
Altitude above sea level	1500 m
Strike direction	NE-SW
Slope	2%/0.5%
Design speed	80 km/h

Table 1
Physical mechanic data of Chinese rock mass grade.

Rock mass grade	Weight (kN/m^3)	Coefficient of elastic resistance (MPa/m)	Modulus of deformation (GPa)	Poisson's ratio	Internal friction angle (°)	Cohesive force (MPa)
I	26–28	1800–2800	>33	<0.2	>60	>2.1
II	25–27	1200–1800	20–33	0.2–0.25	50–60	1.5–2.1
III	23–25	500–1200	6–20	0.25–0.3	39–50	0.7–1.5
IV	20–23	200–500	1.3–6	0.3–0.35	27–39	0.2–0.7
V	17–20	100–200	1–2	0.35–0.45	20–27	0.05–0.2
VI	15–17	<100	<1	0.4–0.5	<20	<0.2

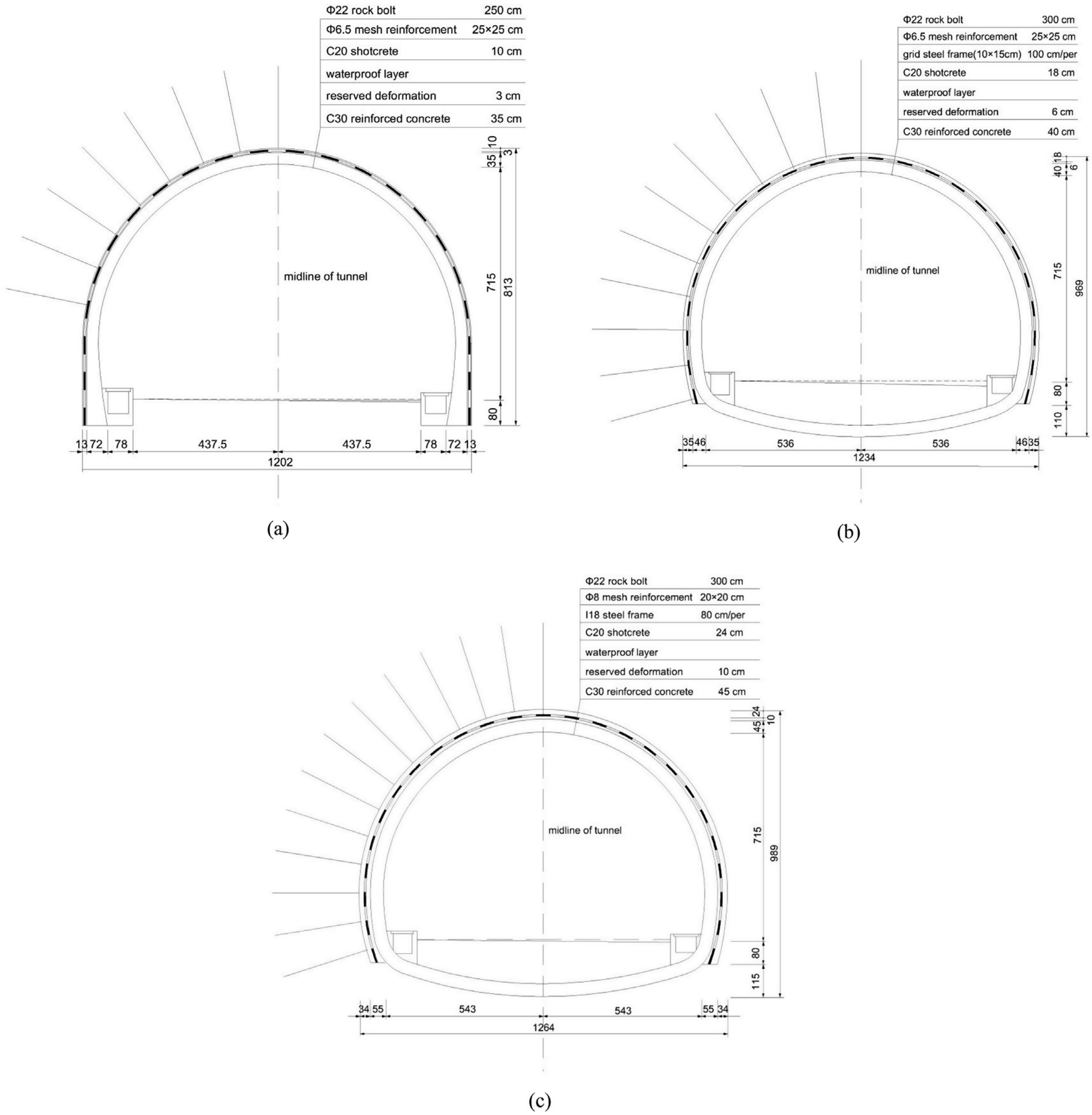

Fig. 1. The Chinese highway tunnel. a) The rock mass of Grade III, b) The rock mass of Grade IV, c) The rock mass of Grade V. Note: the unit of measure of dimension is centimeter (cm).

is used in the middle section of the tunnel (3000 m in length). Taking rock mass grades and pavement types into consideration, five different sections in the tunnel are defined as 'Section a', 'Section b', 'Section c', 'Section d' and 'Section e', as shown in Table 3.

As shown in Table 3, the rock mass grades or pavement types are different in different sections. So different energy and material inputs will come out. In order to compare the potential influences of rock mass grade and pavement types on GHG emission, five different functional units are proposed in this paper. The definition of Functional unit A is '1-m Chinese highway tunnel in 'Section a' with 100-year lifetime'. Similarly, Functional units B-E are defined alphabetically with respect to the Section b-e. The midpoint characterization factor for climate change is GWP-100, which indicates the amount of additional radiative forcing integrated over 100 years caused by an emission of 1 kg of GHG. (Huijbregts et al., 2016).

Table 3
Rock mass grades and pavement types in different sections.

Section	a	b	c	d	e
Tunnel mileage (m)	K0+000-K0+500	K0+500-K0+800	K0+800-K3+500	K3+500-3+850	K3+850-K4+000
Rock mass grade	III	III	IV	IV	V
Pavement type	Asphalt pavement	Concrete pavement	Concrete pavement	Asphalt pavement	Asphalt pavement

2.3. System boundary

The system boundary is shown in Fig. 2. The life cycle of a tunnel is divided into three stages - the construction stage, the operation stage and the maintenance stage. It should be noted that the extraction, production and transportation of upstream materials and energies also generate GHG emissions. But the emissions are finally consumed in the construction stage, the operation stage and the maintenance stage. The GHG emissions of the upstream stages are finally allocated into the three stages, which will help to analyze the indirect emissions of the three stages.

Some assumptions have to be made due to the complex processes of construction activities (Ortiz et al., 2009). The transportation distance of materials between market and tunnel site is assumed to be 100 km. The extra time consumption caused by pavement irregularity, floppy ground, muddy land, sharp turn and abrupt sloop have been considered in the *Highway Engineering Budget Quota*. It is hard to estimate the distance of transporting the construction machineries to the construction site or the distance among sites, so the GHG emissions from the two transportation activities are excluded. Fuel consumption of material transportation is relative to the volume or mass of material consumption per meter in the tunnel. As depicted in Table 3, the functional units are located in different tunnel zones. With increase of the distance between the tunnel portal and the functional unit, fuel consumption rises accordingly. In order to eliminate the influence of transportation distance difference on different functional units, the fuel consumption of transportation is apportioned due to the ratio of consumed material mass per functional unit to the total transportation mass.

As for waste disposal, only blasted rocks are considered. The actual waste of materials, diesel and packaging are excluded in the study due to poor data. It is assumed that blasted rocks are crushed 10 km away from the tunnel site. Sand, gravel and aggregate chips are recycled from the blasted rocks. In the construction stage, 100% of the gravel and aggregate chips as well as 50% of the sand are recycled.

Only the electricity consumption of ventilation and lighting is taken into consideration at operation stage. The lighting design reference year is 2029 and the basic traffic volume of the double-track tunnel is 19,549 Passenger Car Units one day (PCU/d). In different weathers, several lighting conditions are designed, based on the data from the tender. Jet ventilation is used at operation stage.

The total design life of a Chinese highway tunnel is usually no less than 100 years. Thus, this study excludes the tunnel deconstruction stage. The tunnel maintenance in this paper refers to the tunnel pavement replacements. The service life periods of asphalt pavements and concrete pavements are set as 15 and 25 years respectively. The pavements in the tunnel will be replaced six/three times over 100 years.

In order to avoid unlimitedly tracing GHG emissions, the emissions from the manufactures of transportation machines and off-road machines are excluded in the study. Construction machineries are usually used in several construction sites. The depreciation of these machines is not within consideration. The GHG emissions caused by workers are ignored owing to its small amount. Meanwhile, the GHG emissions of preparation, control and monitoring are excluded as well.

2.4. Inventory data

Table 4 and Table 5 summarize the inventory data source, assumptions and allocation at construction stage and operation stage. In order to explain the calculating processes of material consumption, an example about tunnel excavation is given. As for the rock mass of Grade III, the excavation of 100-m^3 stones in the tunnel will consume 0.046-m^3 woods, 0.014-t steel, 98.5-kg explosives, 25-m^3 water and 1.3-machine-team electrical air compressor. These data are from *Highway Engineering Budget Quota*. The electricity consumption data of air compressors is 699 kWh per machine-team which is directly collected from *National Unified Machine-team Expense Standard*. The excavation area for the rock mass of Grade III is 78.83 m^2 according to the tender. So the excavation of 1-m Chinese highway tunnel for the rock mass of Grade III consumes 0.036-m^3 woods, 0.011-t steel, 77.6-kg explosives, 19.7-m^3 water and 716-kWh electricity (see Table 6).

The upstream life cycle inventory data are mainly from Chinese Life Cycle Database (CLCD). CLCD represents the average emission level of the Chinese market. Domestic raw materials and imported materials are distinguished. As for imported materials, models are built based on the Ecoinvent and European life cycle database (ELCD) (Cooper et al., 2012). Domestic materials are classified based on technology and company size, and then models are established with collected data. Finally, the average emission level of the Chinese market is formed by taking the weighted average Chinese

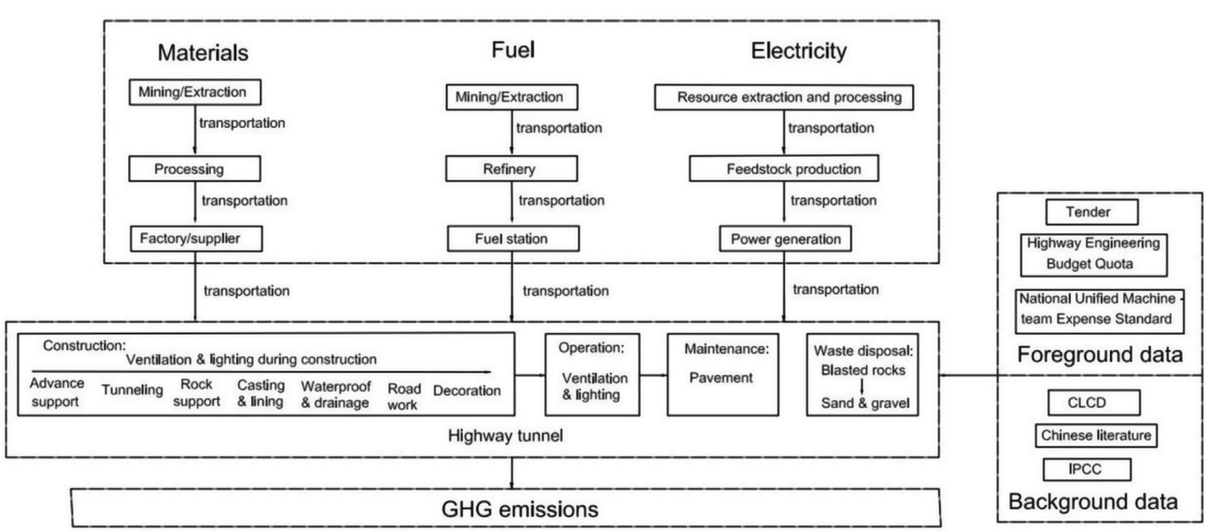

Fig. 2. System boundary of the Chinese highway tunnel.

Table 4
Inventory data sources, assumptions and allocation of the foreground data at construction stage.

Process	Input	Data sources	Comments
Advance support	Cement, electricity, diesel, steel, sand, gasoline	Tenders, *Highway Engineering Budget Quota*, literature	Advanced support includes advanced ductile grouting and rock bolt. Advanced ductile grouting is used for the surrounding rock of Grade V. Rock bolt is applied to the surrounding rock of Grade IV. No advance support is needed for the surrounding rock of Grade III.
Tunneling	Explosive, electricity, steel	Tenders, *Highway Engineering Budget Quota*, product data	Tunneling process comprises of drilling, blasting, scaling, loading and transportation. The excavation areas for rock mass of Grade III, Grade IV and Grade V are 78.33 m^2, 97.48 m^2 and 101.72 m^2. Air-leg drill, matched with air compressors, is used to drill holes.
Rock support	Steel, cement, sand, gravel, diesel, electricity	Tenders, *Highway Engineering Budget Quota*	The rock bolt for the rock mass of Grade III is 2.5 m long, while the rock bolt for the rock mass of Grade IV and V are 3 m long. Construction of shotcrete obeys the requirements of *Chinese Specifications for Bolt-shotcrete Support* (The PRC Ministry of Construction, 2015). Grid steel frames are used for the rock mass of Grade IV. The rock mass of Grade V requires I18 steel frames.
Waterproof & drainage	Steel, high-density polyethylene (HDPE), polypropylene (PP), cement, sand, gravel	Tender, *Highway Engineering Budget Quota*, site data	Plastic blind drain refers to the lateral MF1435 plastic transverse furrow. The material of drain pipes is HDPE. The waterproof bands and ribbons are applied in construction joint, expansion joint, settlement joint. The standard and dosage are obtained from the tender.
Casting and lining	Cement, steel, sand, gravel, diesel, electricity	Tender, on-site data, *Highway Engineering Budget Quota*	Most of the material consumption data are obtained from the tender. All of the concrete used in construction are provided from the self-built concrete batching plant 500 m away from the tunnel site. Fuel consumption of every additional 1 km or 0.5 km in transportation distance follows the *Highway Engineering Budget Quota*. Fuel consumptions of transportation vehicles in idle load are included in the quota.
Road work	Steel, sand, cement, gravel, mineral powder, aggregate chips, PP, gasoline, diesel, electricity	Tender, *Highway Engineering Budget Quota*	As for the asphalt pavement, the top layer is 10 cm thick of asphalt mixed material; the subsurface is 26 cm thick of concrete slab. The concrete base is 15 cm thick of concrete. For the sections without inverted arch, the concrete leveling course is 10 cm thick of concrete, or the concrete base will be replaced by the backfill of inverted arch.
Decoration	Steel, cement, tile, sand, paint	Tender, *Highway Engineering Budget Quota*	The size of one tile is 430 × 220 × 8 mm. The consumption data of tiles and paint are obtained from the tender.
Ventilation & lighting in construction	Electricity	Tender, *Highway Engineering Budget Quota*	The energy consumption of the tunnel ventilation and lighting in construction follows the *Highway Engineering Budget Quota*. Electricity power is supplied by the central China power grid.

Table 5
Inventory data sources, assumptions and allocation of the foreground data at operation and maintenance stage.

Process	Inputs	Data source	Allocation
Ventilation & lighting	Electricity	Tender, *Guidelines for design of ventilation of highway tunnels* (China Merchants Chongqing Communications Technology Research & Design Institute Co. LTD, 2014)	Annual consumption per year is 2280 MWh. Weather conditions, including sunny days and cloudy days in daytime and nighttime are considered. The lighting designs, the luminance outside the tunnel and lighting parameters are all obtained from the tender.
Pavement	Crushed aggregate, cement, steel, PP, PE, diesel, electricity	Tender, *Highway Engineering Budget Quota*	Concrete pavements and asphalt pavements are respectively replaced three times and six times within 100 years. Sand and crushed aggregate are bought from the market.

Table 6
Inventory data source, assumptions and allocation of the background data.

Process	Data source	Comments
Material production	Chinese literature (Gao, 2012; Shen et al., 2016; Zhang, 2013), Intergovernmental Panel on Climate Change (IPCC), CLCD database	Crushed aggregates used in construction are mainly from locally crushed blasted rocks and part of the sand is from the market. The data of blasted rock recycle were obtained from the *Highway Engineering Budget Quota*. The crushed aggregation at maintenance stage is bought from the market.
Production of electricity, gasoline and diesel	Government notice, IPCC	Chinese power grids are classified into central China power grid, northern China power grid, eastern China power grid, northwestern China power grid and southern China power grid. Taking the tunnel site into consideration, the electricity is supplied by the central China power grid. The emission factor of electricity is obtained from the baseline emission factor of Chinese regional power grids in 2014. (National Development and Reform Commission of Climate Change, 2015) The emission factors of diesel and gasoline are from the IPCC.
Material transportation	IPCC	The distance between market and the tunnel site is assumed to be 100 km. Lorry>15 t.

market share into consideration. CLCD covers thousands of unit processes and products. Main products are listed as follows: energies, ferrous metals, nonferrous metals, inorganic metallic materials, inorganic chemicals, organic chemicals and waste handling. In unit processes, consumption data of raw materials are mainly from industry statistics or technical literature. The emission data in CLCD are obtained mainly from Chinese national census statistic of pollution sources, partly from calculated chemical equilibrium. Besides, data from Chinese academic literature could supplement to the database data of CLCD if the emission data in CLCD is

incomplete.

2.5. Data quality analysis

Different data quality grades are used to characterize the data. This method has been used in other life cycle study (Huang et al., 2015). The types and marginal errors are defined as follows.

High-quality Data: Steel, cement, HDPE, explosive, asphalt, tile, sand, gravel, mine powder, PP. These data were directly obtained from the tender or *Highway Engineering Budget Quota*. The marginal data error was estimated as 10%.

Medium-quality Data: Crawler excavator, wheeled loader, road roller, shotcrete machine, transit mixer truck, truck, watering cars, alternating current welding machine, air compressor, sliding form concrete paver, concrete groove cutter, concrete cutting machine, pavement broker, the energy consumption in ventilation and lighting at construction stage. These data were calculated based on *Highway Engineering Budget Quota* and the cost budget of the national unified construction machine team. The marginal data error was estimated as 30%.

Low-quality Data: The electricity consumption data of ventilation and lighting at operation stage. The marginal data error was estimated as 50%.

3. Results

3.1. GHG emissions of the Chinese highway tunnel

Fig. 3 shows the GHG emissions of different stages (processes) in 100 years. The 4-km long Chinese double-track four-lane highway tunnel emits around 375.5 thousand tons of $CO_{2\ eq}$. The tunnel ventilation and lighting at operation stage plays a leading role in the life cycle which shares a proportion of 56.12% of the total emissions. The maintenance stage contributes about 12.99% of the emissions while the construction stage is responsible for 30.89% of the GHG emissions. The three processes with the highest GHG emissions at construction stage are casting & lining (27.25%), rock support (25.33%) and road work (22.03%). Moreover, tunneling and waterproof & drainage process are responsible for 8.54% and 8.47% of the GHG emission at construction stage. A similar case of GHG emission ratio over its whole life cycle is the Swedish Norra Lanken Tunnel, whose GHG emission contributions are 36% (construction stage), 56% (operation stage) and 8% (maintenance stage) (Miliutenko et al., 2012).

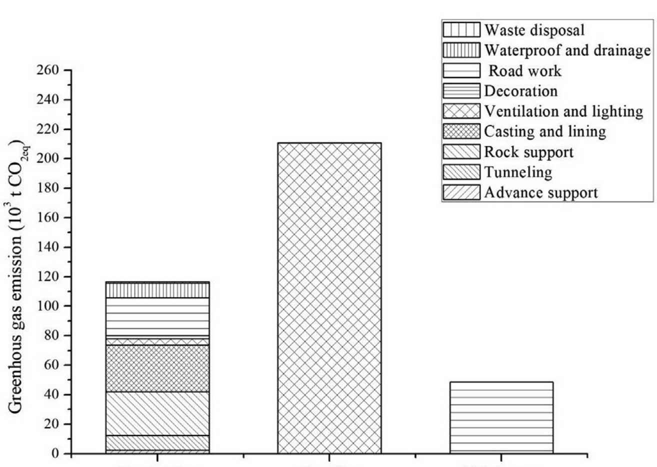

Fig. 3. GHG emissions in different stages (processes) of the tunnel.

3.2. The hotspots of Chinese highway tunnels

Table 7 presents the inputs of materials and energies in each functional unit. Fig. 4 shows the GHG emissions of five functional units based on the data quality analysis. The GHG emission sequence of the functional units is E > D > A > C > B. Off-road machinery emits 57 t - 60 t $CO_{2\ eq}$ per 1-m tunnel. The GHG emissions from materials are from 24 t to 52 t $CO_{2\ eq}$ per 1-m tunnel. The contribution of transportation vehicles to the GHG emissions is weak, smaller than 1.5 t $CO_{2\ eq}$ per 1-m tunnel. As for Functional unit E, emissions from materials grow greatly compared with other functional units. Off-road machineries of Functional unit B are responsible for 66.96% of the GHG emissions.

Fig. 5 shows the relative distributions of GHG emissions from materials and energies. For the five functional units, the electricity consumption accounts for 52%–69% of the total emissions, while the cement contributes 25%–31% of the total GHG emissions. Cement and electricity contribute more than 81% of the total GHG emissions. Table 8 analyzes the absolute emissions from the materials and energies.

Asphalt pavement is used for Functional unit A, D and E. The GHG emissions of Functional unit D and E increase by 6 t $CO_{2\ eq}$ (6.23%) and 17 t $CO_{2\ eq}$ (17.59%) compared with Functional unit A. The increments of total GHG emissions from steel, cement and electricity are 5.78 t and 16.58 t $CO_{2\ eq}$, respectively. The GHG emissions from steel of Functional unit E is 10.53 t and 7.26 t $CO_{2\ eq}$, larger than Functional unit A and D.

Concrete pavement is applied for Functional unit B and C. The GHG emissions of Functional unit C is 11.03 t $CO_{2\ eq}$ larger than B. The increments from steel, cement and electricity are 10.50 t $CO_{2\ eq}$ in total. GHG emission increase is mainly from steel, cement and electricity with the increase of rock mass grade.

4. Discussion

The GHG emissions of 1-m 1-lane tunnel in this study were 20.51 t –28.36 t $CO_{2\ eq}$. The result is obviously higher than the GHG emissions of Norwegian tunnels. Huang et al. reported that the 1-m standard Norwegian tunnel consumes 82 MWh of electricity (Huang et al., 2015). If the GHG emission level from this electricity is in line with the Chinese regional power grid level, the GHG emission of 1-m 1-lane standard Norwegian tunnel caused by electricity will reach 39.8 t $CO_{2\ eq}$. This result will be far more than the GHG emissions reported by Huang et al. or this study. It is because that there is large distinction between the national electricity emission level of China and Norway. 50% of the manufacturing sectors in Norway use hydropower and almost 99% of the Norwegian electricity are supplied by hydropower. As a result, electricity consumption contributes very little to the GHG emissions in Norway (Huang et al., 2015). However, coal still takes up more than half of the Chinese primary energy consumption, used mainly for thermal power. (National Energy Administration of China, 2016) Chinese electricity industry contributes more than 40% of the GHG emissions in the country (Su et al., 2015). Therefore, high emission level of Chinese power grid is a serious disadvantage to the emission reduction of Chinese tunnels. With the implement of the Chinese national carbon trading scheme, China decided to propel the clean and sustainable development of power grids. Large emitters of GHG are limited on emission quotas although they have the economic freedom to reduce emissions or purchase emission allowances from other emitters (Liu et al., 2015). Top GHG emitting industries including cement manufactures, steel productions and coal-fired power plants will be involved. It will be a great benefit for the carbon reduction of tunneling industry if the upstream materials and energies are cleaner.

Table 7
Inputs of 1-m Chinese highway tunnel in the life cycle.

Material and energy	Unit	Functional unit A	Functional unit B	Functional unit C	Functional unit D	Functional unit E
Steel	kg	724	859	2608	2473	6357
HDPE	kg	182	182	182	182	182
Cement	kg	42264	30084	38639	44249	47869
Explosive	kg	155	155	150	150	62
Asphalt	kg	1443	32	25	1431	1431
Ceramic	kg	173	173	173	173	173
Sand	kg	85913	57450	81070	94134	100628
Gravel	t	116	107	130	125	133
Mineral powder	kg	1442	0	0	1442	1442
Aggregate chips	m^3	3	0	0	3	3
PP	kg	19	19	19	19	19
Electricity	MWh	59	58	59	60	61
Gasoline	kg	26	13	9	19	19
Diesel	kg	837	581	766	938	1005

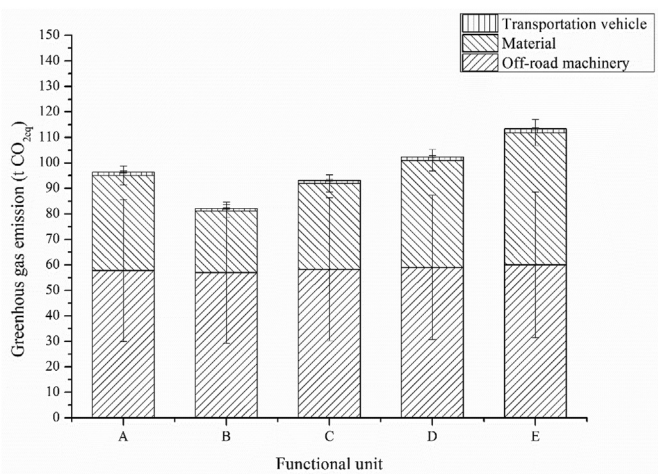

Fig. 4. GHG emission results of five functional units.

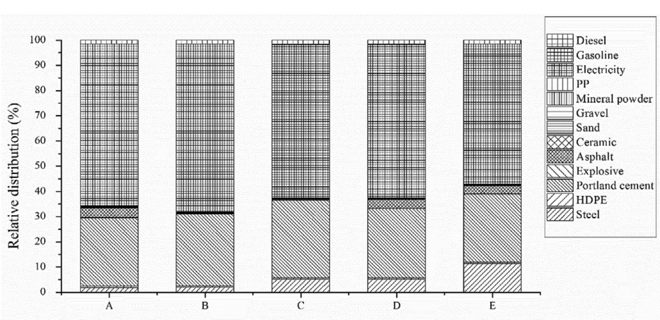

Fig. 5. Relative contribution of each material and energy to the GHG emission.

One efficient way to reduce GHG emissions is to apply energy-saving technologies. In the case of this study, the operation stage, a key stage of GHG emission, accounts for 56.12% of the GHG emissions in the whole life cycle. The operation activities, including tunnel ventilation and lighting, stay the same in different functional units. Choosing energy-saving ventilation and lighting technology will benefit a lot to the carbon reduction of tunnels. For example, based on ten-year energy saving technology research, it is found that the effective use of natural wind will reduce more than 20% of the operation ventilation electricity consumption annually for the tunnel in climate separation zones (Guo et al., 2016, Zhang et al. 2018). Another example is about the strategic role of tunnel pavement in lighting energy consumption. The tunnel lighting system, which is energy-intensive but essential, provides visual guidance for the moving cars. Recent papers found that lighter color of the pavement improves the visibility for the tunnel users, with lower installed power and electrical energy consumption (Moretti et al., 2017b, 2016).

Pavement type also plays an important role in the GHG emissions of tunnels. There are two types of pavements in the tunnel: asphalt pavement and concrete pavement. The study indicates that asphalt pavement will generate more GHG emissions than concrete pavement as for the same grade of rock mass. In this study, concrete pavements will be replaced three times in 100 years while the replacement frequency of asphalt pavements will be doubled. Finally, frequent pavement replacements lead to higher environmental costs. The service lives of pavements are set according to the operation practice of Chinese highways. The service life of the pavement structure has been continuously improved, and it has gradually developed sustainably. In a word, the carbon reduction of pavements will benefit from the technical developments in construction and maintenance.

This paper also finds that the emission differences among the functional units are mainly from materials as shown in Fig. 4. It explains where the additional GHG emissions come from when rock mass grades get worse. Higher grade of rock mass means more unsteady or softer tunnel rock. As for rock mass of poor quality, more materials are needed to reach design requirements. For example, the rock mass of Grade III needs no advance support or steel frame. In contrast, the rock mass of Grade IV and V need advance support and consume certain steel frames. With the increase of material inputs, the GHG emissions rise accordingly. Compared with Functional unit A (rock mass Grade III), the GHG emissions of Functional unit D (rock mass Grade IV) and E (rock mass Grade V) increase by 6.23% and 17.60%. In order to explore the relationship between material consumptions and GHG emissions, the values of GHG emissions and total mass of materials are provided in Fig. 6. Then, correlation analyses are conducted, and the Pearson correlation coefficient of the total GHG emissions and the GHG emissions of materials is 1.000 ($P = 0.000^{**}$). The Pearson correlation coefficient of total GHG emissions and total mass of materials is 0.967 ($P = 0.007^{**}$). It implies more attentions should be focused on the material inputs for the tunnels with poor rock mass conditions. Tunnel designs should be optimized to reduce the consumptions of materials especially cements and steel.

Still, some limitations of this paper need to be clarified. It is inaccurate to claim that a tunnel can represent all tunnels in a country, especially when the country has thousands kilometers of tunnels. The authors don't have such biased expressions. Instead, the authors have clear minds about the complex situations of

Table 8
Absolute GHG emissions of different functional units.

Material/Energy	Absolute GHG emissions (kg $CO_{2\text{-eq}}$)				
	Functional unit A	Functional unit B	Functional unit C	Functional unit D	Functional unit E
Steel	1353	1606	4877	4624	11,887
HDPE	487	487	487	487	487
Portland cement	29,684	21,130	27,138	31,078	33,621
Explosive	41	41	39	39	16
Asphalt	4671	104	81	4631	4631
Ceramic	239	239	239	239	239
Sand	344	230	324	377	403
Gravel	348	321	391	375	398
Mineral powder	192	0	0	192	192
PP	45	45	45	45	45
Electricity	57,188	56,555	57,772	58,311	59,298
Gasoline	50	24	17	36	37
Diesel	1817	1262	1663	2036	2183
Total	96,529	82,247	93,281	102,544	113,511

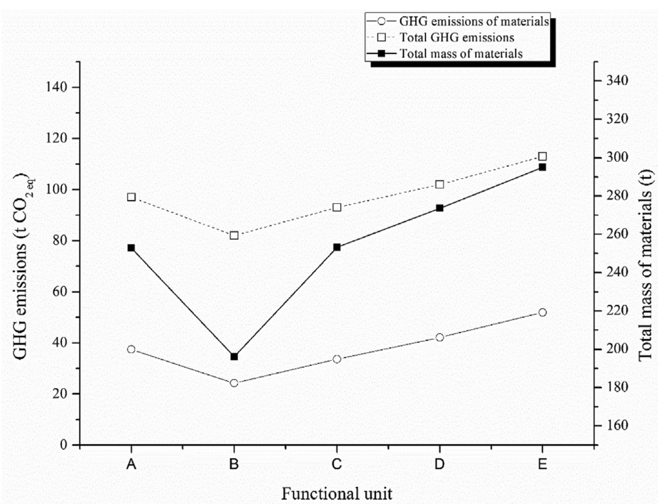

Fig. 6. GHG emissions and the total mass of materials.

geological conditions, tunnel designs and construction activities in different tunnels. What's more, some other geotechnical information about faults, bedding and even karst stratum are not included in the study. Consistent efforts are paid to take these factors into consideration. The authors also want to underline that the GHG emissions of this tunnel has the features of common Chinese tunnels. The designs, construction and maintenance of the tunnel were accomplished by Chinese companies conforming to the Chinese regulations. Another important factor is that the upstream products and energies are mainly produced in China. Their emission levels reflect the energy structure and industry technology of the Chinese market. The authors are making efforts to collect the information of large numbers of tunnels in China. The transition mechanisms of the GHG emissions in different rock mass grades are waiting to be discovered.

5. Conclusions

The originality of the work lies in its consideration of different rock mass classifications. For the first time, rock mass classification which plays a significant role in underground engineering is discovered to be an important factor affecting the GHG emissions of tunnels. The analysis identifies the dependence of the LCA of tunnels on the type of rock mass. Main conclusions are as follows.

Firstly, the 4-km long Chinese double-track four-lane highway tunnel emits around 375.5 thousand tons of $CO_{2\ eq}$. More than half of the total GHG emissions are from tunnel ventilation and lighting at operation stage. The maintenance stage contributes about 12.99% of the emissions while the construction stage accounts for 30.89% of the GHG emission. At construction stage, casting & lining (27.25%), rock support (25.33%) and road work (22.03%) comprise most of the GHG emissions. Considering the large contribution of the operation stage to the GHG emissions, energy saving technologies aiming at tunnel ventilation and lighting will efficiently stimulate the carbon reduction of Chinese tunnels.

Secondly, cement and electricity contribute more than 81% of the emissions. When the rock conditions get poorer, the GHG emissions increase sharply. The GHG emissions of the functional units are from 82 t to 113 t $CO_{2\ eq}$. It is found that the emission differences among the functional units mainly result from materials. Correlation analyses show that the Pearson correlation coefficient of the total GHG emissions and the GHG emissions of materials is 1.000 ($P = 0.000^{**}$). It implies more attentions should be focused on the material inputs for the tunnels with poor rock mass conditions. Tunnel designs should be optimized to reduce the consumptions of materials especially cements and steel.

Thirdly, asphalt pavement will generate more GHG emissions than concrete pavement as for the same grade of rock mass grade. The service life of asphalt pavements is much shorter than concrete pavements. As a result, frequent pavement replacements lead to higher environmental costs.

Conflicts of interest

None.

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